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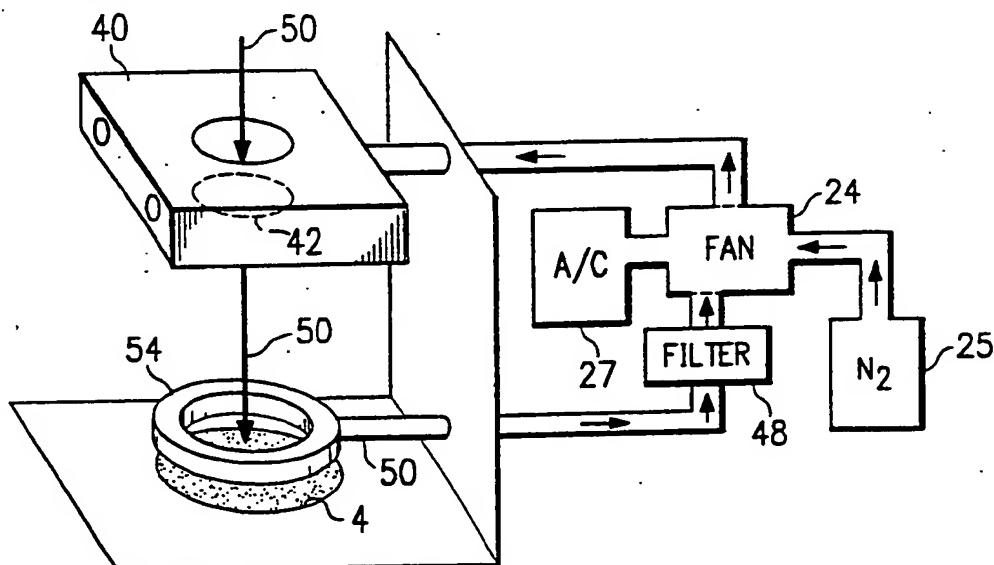
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(54) Title: CONTROLLED GAS FLOW FOR SELECTIVE LASER SINTERING



(57) Abstract

An apparatus for fabricating parts by selective laser sintering is disclosed, which includes a baffle (40) for directing gas at the target surface (4). The gas is preferably controlled in temperature to cool, by convection, a layer of heat-fusible powder after it has been selectively laser sintered, to the temperature of the part formed in prior layers. The cooling preferably occurs prior to the application of the next layer of powder. The baffle (40) directs gas flow towards the center of the target surface (4), and exhaust ports are provided on multiple sides of the target surface (4) so that the gas flow is substantially symmetric at the target surface (4). A ring exhaust hood (54) may be suspended over the target surface, so that uniform gas flow may result and so that powder may be disposed over the target surface by way of a counter-rotating roller (18). The baffle (40) may direct the gas directly at the target surface, or may be constructed so that the gas spirals toward the target surface (4) in cyclonic fashion; further alternative baffles can be used to direct the gas at the target surface in a non-uniform, fashion, including turbulent or arbitrary flow patterns.

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CONTROLLED GAS FLOW FOR SELECTIVE  
LASER SINTERING

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5        This invention is in the field of the manufacture of articles such as parts, and is more particularly directed to selective laser sintering.

Background of the Invention

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      Selective laser sintering is a relatively new method for producing parts and other freeform solid articles in a layer-by-layer fashion. This method forms such articles by the mechanism of sintering, which refers to any process by which  
15        particulates are made to form a solid mass through the application of external energy. According to selective laser sintering, the external energy is focused and controlled by use of a laser to sinter selected locations of a heat-fusible powder. By performing this process in layer-by-layer  
20        fashion, complex parts and freeform solid articles which cannot be fabricated easily (if at all) by subtractive methods such as machining can be quickly and accurately fabricated. Accordingly, this method is particularly beneficial in the production of prototype parts, and is  
25        particularly useful in the customized manufacture of such parts and articles directly from computer-aided-design data bases.

      Selective laser sintering is performed by depositing a  
30        layer of a heat-fusible powder onto a target surface; examples of the types of powders include metal powders, polymer powders such as wax that can be subsequently used in investment casting, ceramic powders, and plastics such as ABS plastic, polyvinyl chloride (PVC), polycarbonate, and other  
35        polymers. Portions of the layer of powder corresponding to a cross-sectional layer of the part to be produced are

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exposed to a focused and directionally controlled energy beam, such as generated by a laser having its direction controlled by mirrors, under the control of a computer. The portions of the powder exposed to the laser energy are  
5 sintered into a solid mass in the manner described hereinabove. After the selected portions of the layer have been so sintered or bonded, another layer of powder is placed over the layer previously selectively sintered, and the energy beam is directed to sinter portions of the new layer  
10 according to the next cross-sectional layer of the part to be produced. The sintering of each layer not only forms a solid mass within the layer, but also sinters each layer to previously sintered powder underlying the newly sintered portion. In this manner, the selective laser sintering  
15 method builds a part in layer-wise fashion, with flexibility, accuracy, and speed of fabrication superior to conventional machining methods.

The selective laser sintering process, and an apparatus  
20 for performing the process, are described in further detail in U.S. Patent No. 4,863,538, issued September 5, 1989, U.S. Patent No. 4,938,816, issued July 3, 1990, U.S. Patent No. 4,944,817, issued July 31, 1990, and PCT Publication WO 88/02677, published April 21, 1988, all of which are  
25 incorporated herein by this reference.

A problem faced by those in the selective laser sintering field is the warpage and shrinkage of the part due to thermal effects. Such warpage may occur where the part  
30 itself warps, for example where a bottom flat surface curls up at the edges to become a curved surface, concave up. It is believed that significant causes of this warpage include the thermal shrinkage of the sintered layer from its temperature during sintering to its post-sintering  
35 temperature, and, in some cases, the reduction in volume of a layer as it passes through the phase change from liquid to

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solid. The reduction in volume of the layer just sintered, whether by phase change or by a drop in temperature, causes the top of the part to contract. The bottom of the part, being immersed in a fairly good thermal insulator, has already contracted, so the contraction of the top layer induces a stress in the part, which results in curling of the part. In addition, uneven cooling of the part during its layer-wise manufacture, for example where top layers of the part are cooled more quickly than bottom layers, has been observed to cause warpage and curling.

It has been observed that control of the temperature of the article being produced is an important factor in reducing such warpage. An apparatus for controlling the part temperature is described in the above-referenced PCT Publication WO 88/02677, which provides a draft of temperature-controlled air through the target area (i.e., through the powder and the part being produced). Such control by this draft is believed to reduce the temperature differential that the part is exposed to during and after the sintering process, reducing shrinkage from cooling, and to maintain the temperature of previously sintered layers at high enough temperature to allow relaxation.

Another significant problem faced by those in the field of selective laser sintering is undesired growth of the part being produced beyond the volume defined by the energy beam. As is well known, the spot size of a laser beam can be made quite small, so that according to the selective laser sintering method which defines the volume of the part by the laser scan, the resolution of the part being produced can theoretically be quite high. However, conduction of heat resulting from the sintering can cause particles of the powder outside the laser scan to sinter to the directly sintered portion. This causes the cross-sectional layer to be larger than that defined by the laser scan. In addition,

growth can occur from layer to layer, for example where sufficient heat from sintering remains in the sintered portion of the layer at the time that the next layer of powder is disposed thereover, so that the next powder layer sinters to the prior layer without exposure to the laser beam. The downdraft apparatus described hereinabove was found to provide transfer of bulk heat from the layer previously sintered, reducing the extent of such extralayer growth.

10

However, the ability of convection techniques through the powder and part to uniformly control the temperature of the layer being produced is quite limited. This is due to the undefined and non-uniform path that the air draft necessarily must follow as it passes through the part being produced (the definition of the part controlling the path of the draft). Accordingly, another technique that has been used in attempts to control the temperature of the part being produced has been radiant heaters placed near the target surface. Such radiant heaters have included floodlamps, quartz rods, and conventional flat radiant panels. In addition, copending U.S. application S.N. 611,309, entitled "A Radiant Heating Apparatus for Providing Uniform Surface Temperature Useful in Selective Laser Sintering", assigned to DTM Corporation and incorporated herein by this reference, describes an improved radiant heating apparatus for use in a selective laser sintering apparatus.

In conventional machines used in selective laser sintering, gas has been directed to flow in a direction parallel to the target surface at which the selective laser sintering is taking place. This gas flow is primarily used during the selective laser sintering of each layer of the part being produced; in addition, such gas flow is continued after the sintering of a layer, and prior to the application of the next layer of powder. The gas flow is intended to

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remove air-borne material such as smoke or dust from the location of the selective laser sintering, and also to provide convective cooling of sintered portions of the part bed (i.e., the powder overlying part piston 6, the top of which is the target surface), prior to deposition of a new layer.

Referring to Figure 1, an example of this prior apparatus will now be described. The apparatus shown in Figure 1 is a schematic representation of the SLS Model 125 DeskTop Manufacturing system manufactured and sold by DTM Corporation. The apparatus of Figure 1 includes a chamber 2 (front doors and the top of chamber 2 are not shown in Figure 1, for purposes of clarity), within which the selective sintering process takes place. Target surface 4, for purposes of the description herein, refers to the top surface of heat-fusible powder (including portions previously sintered, if present) disposed on part piston 6. The vertical motion of part piston 6 is controlled by motor 8. Laser 10 provides a beam 50 which is reflected by galvanometer-controlled mirrors 12 (only one of which is shown for clarity), in the manner described in the U.S. Patents referred to hereinabove. Powder piston 14 is also provided in this apparatus, controlled by motor 16. As described in the above-referenced PCT Publication 88/02677, counter-rotating roller 18 is provided to transfer the powder to the target surface 4 in a uniform and level fashion.

In operation, the apparatus of Figure 1 supplies powder to chamber 2 via powder cylinder 14; powder is placed into chamber 2 by the upward partial motion of powder cylinder 14 provided by motor 16. Roller 18 (preferably provided with a scraper to prevent buildup, said scraper not shown in Figure 1 for clarity) spreads the powder within the chamber by translation from powder cylinder 14 toward and across target surface 4 at the surface of the powder on top of part piston

6, in the manner described in said PCT Publication 88/02677. At the time that roller 18 is providing powder from powder piston 14, target surface 4 (whether a prior layer is disposed thereat or not) is preferably below the floor of chamber 2 by a small amount, for example 5 mils, to define the thickness of the powder layer to be processed. It is preferable, for smooth and thorough distribution of the powder, that the amount of powder provided by powder cylinder 14 be greater than that which can be accepted by part cylinder 6, so that some excess powder will result from the motion of roller 18 across target surface 4; this may be accomplished by the upward motion of powder piston 14 by a greater amount than the distance below the floor of chamber 2 that target surface 4 is set at (e.g., 10 mils versus 5 mils). It is also preferable to slave the counter-rotation of roller 18 to the translation of roller 18 within chamber 2, so that the ratio of rotational speed to translation speed is constant.

Further in operation, after the transfer of powder to target surface 4, and the return of roller 18 to its original position near powder piston 14, laser 10 selectively sinters portions of the powder at target surface 4 corresponding to the cross-section of the layer of the part to be produced, in the manner described in the above-referenced U.S. Patents and PCT Publication. After completion of the selective sintering for the particular layer of powder, part piston 6 moves downward by an amount corresponding to the thickness of the next layer, awaiting the deposition of the next layer of powder thereupon from roller 18.

Radiant heat panels 20 are provided in this prior apparatus of Figure 1, suspended from the roof of chamber 2 (in a manner not shown). Radiant heat panels 20 in this prior arrangement are conventional flat rectangular heat panels, each of which emit energy per unit area substantially



uniformly across its surface. In this arrangement, radiant heat panels 20 are separated from one another to allow the beam 50 from laser 10 to pass therebetween, and are disposed at an angle relative to target surface 4, to heat target surface 4 so that the surface temperature can be controlled to reduce growth and curling, as described hereinabove.

Referring to Figure 2, a side cross-sectional view of the part piston side of the apparatus of Figure 1 will now be described. An opening 22 is disposed at the top of the rear wall of chamber 2, into which a gas for controlling the temperature of target surface 4 is forced by a fan motor 24. For example, an inert chilling gas, such as nitrogen from a nitrogen source 25, is provided to fan motor 24. Nitrogen source 25 may consist of a dewar containing liquid nitrogen, together with an expander in which the liquid nitrogen expands into a vapor. Fan motor 24 forces the gas into the closed chamber 2 through opening 22 at a controlled temperature, either heated by a heater or heat exchanger or chilled by way of an air conditioning unit. In chamber 2, an exhaust opening 26 is provided near the bottom of the rear wall of chamber 2 so that the gas can circulate through the chamber and either be vented or recirculated. As a result of this configuration, the chilling (or heating, or other temperature modulating gas) circulates through chamber 2 as shown in Figure 2, with the direction of the flow of the gas being substantially parallel with target surface 4 at the bottom of chamber 2.

It should be noted that the configuration of Figures 1 and 2 has been observed to be beneficial in controlling the selective laser sintering process by providing a medium for cooling target surface 4. However, with the chilling gas flowing as shown in Figure 2, significant non-uniformities in temperature have been observed. Such non-uniformities can be of such an extent that growth can occur on one side of target

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surface 4 and the part being produced (e.g., the side closest to exhaust port 24) due to the temperature being too high thereat, at the same time that curling occurs at the other side of target surface 4 (e.g., the side closest to the front of chamber 2) due to the temperature being too cool thereat.

It is therefore an object of this invention to provide an apparatus for selective laser sintering in such a manner that the temperature across the target surface is substantially uniform.

It is a further object of this invention to provide such apparatus in which low temperature materials, such as wax, may be processed by selective laser sintering with high degrees of accuracy.

It is a further object of this invention to provide such an apparatus which allows the gas temperature to be different from the temperature at the target surface, so that the gas may be used to uniformly cool the part being produced.

It is a further object of this invention to provide such an apparatus which allows the use of gas flow and radiant emission from the part to cool the part at the target surface, either uniformly or non-uniformly, as desired.

Other objects and advantages of the instant invention will be apparent to those of ordinary skill in the art having reference to the following specification together with the drawings.

Summary of the Invention

The invention may be incorporated into an apparatus for  
5 selective laser sintering in which a baffle directs gas  
downward to the target surface coaxially with the laser beam,  
with vents disposed on multiple sides of the target surface  
at the bottom of the chamber. The gas may be directed to be  
substantially normal with the target surface; alternatively,  
10 the gas may be baffled to flow downwardly and cyclonically.  
In either case, the flow of gas at the target surface is  
angularly symmetric, so that uniform thermal effects, such as  
cooling, result at the target surface during selective las r  
sintering. The uniform cooling provides the ability to  
15 accurately perform selective laser sintering of low  
temperature materials, such as wax.

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Brief Description of the Drawings

Figure 1 is an isometric and schematic illustration of  
5 an apparatus for selective laser sintering according to the  
prior art.

Figure 2 is a cross-sectional side view of the  
conventional apparatus of Figure 1, illustrating gas flow  
10 therein.

Figure 3 is a cross-sectional diagram of layers of  
powder during the selective laser sintering process,  
illustrating heat transfer therefrom.  
15

Figure 4 is an isometric view and block diagram of an  
apparatus for selective laser sintering according to the  
preferred embodiment of the invention.

20 Figure 5 is an isometric view and block diagram of an  
apparatus for selective laser sintering according to an  
alternative embodiment of the invention.

Figure 6 is a cross-sectional diagram illustrating gas  
25 flow in the apparatus of Figure 5.

Figure 7a is an isometric view of a baffle according to  
an alternative embodiment of the invention.

30 Figure 7b is a cross-sectional view of the baffle of  
Figure 7a, illustrating the gas flow therein.

Figures 8a and 8b, and Figure 9, are cross-sectional and  
plan views, respectively, of an apparatus according to  
35 alternative embodiment of the invention incorporating gas  
distribution plenum and diffuser.

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Detailed Description of the Preferred Embodiments

As indicated hereinabove, the use of gas flow in selective laser sintering has been used for purposes of removal of particulates suspended within the sintering chamber as a result of the sintering process, such suspended particulates including smoke, dust from the heat-fusible powder and the like. In addition, gas flow has been used in an attempt to modulate temperature differences at the target surface, both during and after the sintering process. Convection across the target surface, whether with gas of the same temperature as the target surface or of a cooler temperature, will serve to reduce local temperature gradients caused by the selective laser sintering. However, as noted hereinabove, asymmetric flow across the target surface itself causes temperature non-uniformity. Such non-uniformity can cause less than optimal control of the process, resulting in growth, curling, or both.

20

In addition to the above reasons for providing gas flow in the selective laser sintering process, it has been recently discovered that convection cooling of the target surface after selective laser sintering has been performed for a layer of heat-fusible powder, and prior to the application of the next layer of powder, is quite beneficial, particularly for low temperature materials such as wax. Such cooling is necessary in order to control the thermal history of the part being produced, and improve the resolution and accuracy of the part being formed.

30

The sintering at the selected locations of the heat-fusible powder occurs as a result of the energy provided by the laser beam. After the selective laser sintering is completed for a layer, heat will remain in the layer, particularly in the sintered portions. If the heat from

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sintering is not removed prior to the application and sintering of the next layer, the part being produced will progressively heat up over the duration of the process, which may be many hours. As noted hereinabove, excessive heat can result in the sintering of powder outside of the laser path to the powder directly irradiated by the laser, causing growth of the part outside of its desired boundaries and dimensions. In the case where previously sintered layers retain excess heat from their sintering, such growth may occur from layer to layer. For example, the definition of a top surface of a portion of the part can become inaccurate if excessive heat is retained in the sintered portion, as powder applied over the sintered portion which is not intended to be sintered by the laser may sinter to the sintered portion due to the retained heat, causing growth at this top surface.

The problems of retention of heat in the produced part produces significant problems, particularly where heat is retained non-uniformly over the surface of the layer. Such non-uniformity is especially troublesome for materials which solidify over narrow temperature ranges, as curling may occur at one location of the powder layer while staying molten at other locations. Examples of powder materials having narrow solidification temperature ranges include crystalline polymers, which solidify within a temperature range on the order of one to two degrees Celsius. As noted hereinabove, a particularly beneficial use of selective laser sintering is the production of wax parts used in fabricating investment casting molds according to the "lost wax" method. Standard investment casting waxes include broadband crystalline polymers, which solidify over a temperature range on the order of two to three degrees Celsius.

Referring to Figure 3, the heat transfer mechanisms for a layer of powder 30 after the selective laser sintering of

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portions 32 therein can be considered according to the following steady-state relationship:

$$q_{\text{grad in}} = q_{\text{grad out}} + q_{\text{cond out}} + q_{\text{conv out}}$$

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where  $q_{\text{grad in}}$  is the rate of transfer of heat into layer 30,  $q_{\text{grad out}}$  is the rate at which heat radiates out from layer 30,  $q_{\text{cond out}}$  is the rate at which heat conducts out from layer 30, and where  $q_{\text{conv out}}$  is the rate at which heat is removed from layer 30 by way of convection.

The source of radiation into layer 30 includes the laser, and also such other heaters such as radiant heat panels 20. Since the materials used as heat-fusible powders, especially the polymers noted hereinabove, generally have poor thermal conduction characteristics, the rate  $q_{\text{cond out}}$  of conduction out of layer 30 is negligible (prior to the application of the next layer, as will be described hereinbelow). It is believed that the rate  $q_{\text{grad out}}$  at which heat radiates from layer 30, although significant, will be much less than the rate  $q_{\text{grad in}}$  at which the laser transfers heat into layer 30. In addition, the rate of radiation of heat from layer 30 will likely be non-uniform over the surface of layer 30, as the rate of radiation of unsintered powder differs from that of sintered portions 32.

As a result, a high rate  $q_{\text{conv out}}$  of heat transfer by convection is required to balance the above relationship in order that excess heat does not remain in layer 30 prior to the application of the next layer of powder thereover. Especially for the polymer materials noted above, which have narrow temperature ranges of solidification, the convection must preferably be done in a quite uniform manner. Alternatively,  $q_{\text{cond out}}$  and  $q_{\text{grad out}}$  may be examined in sum across the part surface. Either may be non-uniform across the part surface so long as their sum is consistent across the part

surface, or so long as the rate at which the part approaches the bed temperature is uniform across the bed.

It should be noted that the application of the next  
5 layer of powder over layer 30 will assist in the removal of heat by way of thermal conduction, particularly where the temperature of the powder is less than the temperature of layer 30 after its selective laser sintering. However, in order to reduce the extent of curling, it is preferred that  
10 the powder be preheated, for example while it is located over powder piston 14 in the apparatus of Figure 1, to a temperature which is close to the temperature of the part being produced, so long as the powder can be leveled by roller 18 at such a temperature. Accordingly, the next layer  
15 of powder applied over layer 30 of Figure 3 will also assist in modulating the temperature to that of the preheating, which preferably is close to that of the part being produced.

Referring now to Figure 4, a first preferred embodiment  
20 of the invention for providing symmetric gas flow over a layer of powder will now be described in detail. As in the prior apparatus of Figure 1, a gas source 25 provides the gas which is to circulate within the selective laser sintering chamber to fan motor 24. The gas is preferably inert, so  
25 that ignition and combustion of the powder inside the chamber is prevented. For example, where chilled nitrogen is the gas to be circulated, gas source 25 consists of a dewar for holding liquid nitrogen and an expander to allow the nitrogen to enter the gas phase. Fan motor 24 preferably controls the  
30 temperature at which the gas is to be presented into the chamber, for example by way of air conditioning unit 27. A preferred fan motor 24 is a an American Fan model AF-10 pressure blower.

35 According to this embodiment of the invention, the gas forced by fan 24 enters the chamber via baffle 40. Baffle



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40 is preferably mounted to the roof of the chamber, and has an opening 42 at the bottom out of which the gas forced by fan 24 exits into the chamber in a downward direction. Baffle 40 has a window at its top which is transparent to  
5 laser beam 50; laser beam 50 thus travels through baffle 40, exiting through opening 42. Accordingly, the flow of the gas through baffle 40 is substantially perpendicular to target surface 4, and is directed at the center of target surface 4.

10

Also according to this embodiment of the invention, exhaust vents 44 are located on the floor of the chamber, on multiple sides of target surface 4. In the example of Figure 4, exhaust vents 44 are located on three sides of target  
15 surface 4; no exhaust vent 44 is provided on the side of target surface 4 from which roller 18 (not shown) travels with the powder to be applied over target surface 4, as the powder would fall into such an exhaust vent. Exhaust vents 44 are connected to exhaust manifold 46, which recirculates  
20 the exhaust gas to fan 24. Filters 48 are provided for removal of particulates, such as suspended particles of the powder, smoke and other debris, from the gas exiting the chamber through exhaust vents 44.

25 It should be noted that, for best results, a ring shaped radiant heater as described in the above-referenced U.S. application S.N. 611,309 incorporated herein by this reference, is preferably suspended below baffle 40. Radiant heating of target surface 4 is preferred, even for low  
30 temperature selective laser sintering, as the temperature at target surface 4 which is sufficient to minimize curling may be higher than that at which the powder may be leveled by roller 18.

35 As a result of the configuration of Figure 4, the flow of the gas near the powder at target surface 4 is

substantially parallel to its surface. Furthermore, with the flow of gas directed at the center of target surface 4, and exiting on multiple sides of target surface 4, the cooling of target surface 4 is done in such a manner that the temperature gradient across the layer of powder at target surface 4 is reduced from the prior arrangement of Figure 1, which resulted in hot and cool sides of target surface 4.

The apparatus according to the preferred embodiment of the invention allows for sufficient uniformity in temperature that crystalline polymers such as investment casting wax may be successfully processed by selective laser sintering, with minimal growth and curling. For example, in the selective laser sintering of investment casting wax, the apparatus according to the preferred embodiment cools each layer after selective laser sintering to a temperature on the order of 30 degrees Celsius. This is accomplished by providing nitrogen gas at a temperature of -5 Celsius, and at a flow rate of 190 sccm into the chamber. In this example, the laser power is on the order of 10 to 15 Watts, preferably 11 to 12 Watts, scanning at a speed of on the order of 40 inches per second, and the temperature of the wax powder in the powder cylinder is maintained on the order of 15 degrees Celsius. Selective laser sintering of such wax at these conditions, in the arrangement of the preferred embodiment of the invention, has been successful in producing high quality and accuracy wax parts.

Referring again to Figure 4, additional ports 52 may be provided on the sides of baffle 40, out of which gas will also flow into the chamber, to adjust for non-uniformities in the gas flow within the chamber, or in radiant heat irradiation of the part surface. The location, size and number of ports 52 will depend on the particular environment of the selective laser sintering chamber, and may be determined by experimentation.

It should also be noted that the convective cooling resulting from the embodiment of the invention described hereinabove is intended to be substantially uniform, so that the powder layer is cooled, after its selective laser sintering, to a quasi-equilibrium temperature near that of the part bed (i.e., the previously sintered layers therebelow above the top of part piston 6). Alternatively, by way of ports 52, baffles disposed within baffle 40 which redirect the air flow, or auxiliary fans, convective cooling may be intentionally applied to target surface 4 in a non-uniform manner. Such non-uniform convective cooling can compensate for thermal non-uniformities in the powder layer at target surface 4, such as non-uniform irradiation of the part bed from radiant heaters and from the walls of the chamber. Design of the gas flow from baffle 40 can thus result in a thermally "tuned" combination of the chamber, radiant heaters and gas flow, producing a uniform temperature distribution across the part bed at target surface 4.

20

As noted hereinabove, due to the use of roller 18 to provide a level layer of powder over target surface 4, exhaust vents cannot be disposed on all sides thereof. While the embodiment of Figure 4 provides improved temperature uniformity over the prior apparatus of Figures 1 and 2, further improvement can be achieved by improving the symmetry of exhaust from the chamber. Referring now to Figures 5 and 6, an exhaust according to a second embodiment of the invention will now be described.

30

Figure 5 illustrates ring exhaust 54 located within an apparatus for selective laser sintering as described hereinabove. In this embodiment, ring exhaust 54 is a ring-shaped hood, open on its bottom surface, which is suspended over target surface 4 by a sufficient distance to allow roller 18 (see Figure 1) to travel thereunder and apply a

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layer of powder to target surface 4. Ring exhaust 54 connects to pipe 56 through which the exhaust gases are communicated to outside of the chamber, for filtering through filters 48 and recirculation through fan 24 as in the embodiment of Figure 4. If pipe 56 is insufficient to support ring exhaust 54, a bracket, chains, or other support for ring exhaust 54 may be used to suspend ring exhaust 54 over target surface 4.

10 Referring to Figure 6, the direction of the gas flow from baffle 40 into ring exhaust 54 will be described. It is preferable that ring exhaust 54 have a radius slightly larger than target surface 4 (i.e., the top of part piston 6) for best symmetry of the gas flow over target surface 4, and that  
15 the opening of ring exhaust 54 be at its bottom. As shown in Figure 6 in cross-section, provision of ring exhaust 54 near target surface 4 provides gas flow which flows downward onto to target surface 4 near its center, and then travels substantially parallel with target surface 4 radially outward  
20 toward ring exhaust 54. In addition, since ring exhaust 54 encircles target surface 4, the radial parallel gas flow at target surface 4 is symmetric, and does not have a directional dependence. Further improvement in the uniformity of temperature at target surface 4 is thus  
25 achievable with the embodiment of Figures 5 and 6.

Referring now to Figure 7a, cyclone baffle 60 for directing gas flow downward toward target surface 4, constructed according to another embodiment of the invention,  
30 will now be described. Cyclone baffle 60 is constructed for attaching to the top of the chamber in the selective sintering apparatus of Figure 4 in similar manner as baffle 40, for directing gas flow downward onto target surface 4. As shown in Figure 7a, cyclone baffle 60 is shaped conically,  
35 and has a gas input at its top which is off center. The off-center position of the gas input causes the gas flow within

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cyclone baffle to circulate around the inner surface of baffle 60 in helical fashion, as shown in Figure 7a. As a result, the gas flow emanating from the bottom of cyclone baffle 60 not only has a downward component, but also has a rotational component. The direction of the rotation is not believed to be important.

The rotational effect of the gas flow as it reaches target surface 4 due to the construction of cyclone baffle 60 is intended to further reduce directional dependency of the parallel convection flow, and further improve the uniformity of the temperature of the layer of powder at target surface 4, after it has undergone selective laser sintering, and prior to the application of the next powder layer thereover. It should be noted that cyclone baffle 60 may be used with either of the above-described exhaust systems (i.e., the three exhaust ports 44 of Figure 4, or exhaust ring 54 of Figures 5 and 6).

Further in the alternative, a baffle according to the invention may be constructed and used so that the gas flow directed at target surface 4 has arbitrary or turbulent directional components in the plane of target surface 4. Construction of such baffles is contemplated to be within the level of ordinary skill in the art having reference to this specification; for example, a box such as baffle 40 described hereinabove may have internal baffles for randomizing or making turbulent the gas flow out of the bottom thereof, or may include auxiliary fans therein for accomplishing the same types of randomization or turbulence. The exhausts described hereinabove will be effective to substantially uniformly direct the flow, as a function of angle from the center of target surface 4, in the manner described hereinabove.

Referring now to Figures 8a, 8b and 9, an alternative embodiment of the invention will now be described, in which the gas flow may selectively be uniformly directed toward target surface 4, or directed away therefrom, as desired.

5

It has been discovered that a cooling gas flow is particularly beneficial for low temperature materials, such as waxes, in order to reduce the growth tendency of the fused or sintered portion of the powder, and also to maintain the unfused powder over the powder piston at relatively cool temperatures, so that it remains in powder form and does not agglomerate. It has further been discovered that cooling gas flow is not desirable for some higher temperature materials, as excessive cooling can result in curling of the fused or sintered layer portion. Such curling has been observed in the production of parts from many plastics, including polycarbonate, vinyls, and ABS.

Figure 8a is a cross-sectional view of chamber 102 in which an additive process for producing parts is being performed. In this embodiment of the invention, the additive process is that described hereinabove in which selected portions of a layer of fusible powder at target surface 4 are fused (e.g., sintered) by way of an energy beam (e.g., a laser) according to a cross-section of the part to be produced; subsequent layers of powder are then placed over target surface 4 and similarly fused or sintered, with the fused portion of each layer fusing to that in prior layers to form a three-dimensional part.

30

It is contemplated that other types of additive processes for producing parts may also benefit from the present invention. An example of such another method is described in Sachs, et al. "Three Dimensional Printing of Ceramic Shells and Cores for Metal Casting", Proc. of the 39th Annual Technical Meeting: Investment Casting Institute (1991), pp.

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12:1 - 12:14, incorporated herein by this reference, in which a layer of powder, such as a ceramic powder, is dispensed and a binder material is applied to selected portions of the powder, for example by way of an ink-jet printhead. Another  
5 example of such an additive method is that described in Fussell, et al., "Controlling the Microstructure of Arc Sprayed Shells", Proceedings of the Solid Freeform Fabrication Symposium, (The University of Texas at Austin, 1991), pp. 213-235, incorporated herein by this reference, in  
10 which metals such as zinc, zinc alloys, and steel are arc sprayed onto a masked target surface to form tooling.

The cross-sectional view of Figure 8a is from the front of chamber 102 (with the front-door removed), chamber 102  
15 being similar in construction as chamber 2 of Figures 1 and 4 except to the extent described hereinabove. Figure 9 is a plan view taken looking downward from the top of chamber 102. Target surface 4 is shown at the center of the bottom of chamber 102, and may be scanned by laser beam 50 as shown in  
20 Figure 8a.

Located above Figure 8a is plenum chamber 106, having a top defined by the top of chamber 102, and having front and back sides defined by the front and back of chamber 102.  
25 Removable side panels 140 define the lateral sides of plenum chamber 106, and control whether or not gas flow reaches target surface, as will be described hereinbelow. Side panels 140 are spaced from the side walls of chamber 102, so that exhaust plenums 104 are defined therebetween. Exhaust  
30 ports (not shown) are provided at the top of chamber 102 in communication with exhaust plenums 104, for the removal of gas from chamber 102 in similar manner as described hereinabove.

35 The bottom of plenum 106 is defined by feed panel heaters 130 and target radiant heater 120, in combination.

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Target radiant heater 120 has a hole therethrough by which laser beam 50 can impact selected portions of target surface 4. Referring to Figure 9, target radiant heater 120 is preferably formed in a rectangular panel 122 of fiber board, in which resistive elements are placed in a ring shape concentric with target surface 4. As described in copending U.S. patent application S.N. 611,309, entitled "A Radiant Heating Apparatus for Providing Uniform Surface Temperature Useful in Selective Laser Sintering", assigned to DTM Corporation and incorporated herein by this reference, such a ring-shaped heater transfers heat energy to flat target surface 4 in a highly uniform manner. Feed panel heaters 120 are similarly fabricated, for heating the unfused powder over powder pistons on either side of target surface 4; the shape of the resistive elements in feed panel heaters 120 may be rectangular, as laser beam 50 need not pass therethrough, but it is contemplated that ring-shaped patterns may also be preferable for feed panel heaters 120 to provide heat energy to unfused powder in a uniform manner.

20

In the back wall of chamber 102, and within plenum chamber 106, are inlet ports 108 having diffusers placed thereover. Also within plenum chamber 106 is diffuser 126, which is disposed coaxially with the hole through target radiant heater 120, and which extends from the top of plenum chamber 106 to target radiant heater 120 so that any gas entering plenum chamber 106 (while configured as shown in Figure 8a) must pass through diffuser 126. Diffuser 126, and also the diffusers over inlet ports 108, are intended to restrict the flow of gas therethrough to limit the directionality of the flow exiting the same. An example of the construction of diffuser 126 is of rolled stainless steel, perforated with circular holes of diameter on the order of 0.125 to 0.187 inches, with a density of from 30% to 60% of the surface area of diffuser 126; the diffusers over inlet ports 108 may be similarly constructed.

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In order to have the proper plenum effect, the volume of plenum chamber 106 is preferably as large as practicable, and as such preferably extends as closely as possible to the sides of chamber 102 and to heater panels 120, 130. As a result, with both the plenum effect of chamber 106 and diffuser 126 (as well as over inlet ports 108), the flow of gas out from plenum chamber 106 toward target surface 4 is quite uniform. Upon reaching target surface 4, the gas flows tangentially thereto, radially across target surface 4, and upward through exhaust plenums 104. The direction of gas flow is schematically illustrated by arrows G in Figure 8a.

It is also much preferred that the gas enter plenum chamber in as symmetric a fashion as possible. Accordingly, it is preferred that inlet ports 108 be symmetrically located on the sides of chamber 102 to preclude biasing of the direction of gas flow therethrough.

As in the prior described embodiments, the uniform gas flow provided in this embodiment of the invention provides high uniformity in the cooling of each layer processed by the method, and thus in the precision of the parts produced, with growth and curling minimized. In particular, the configuration of Figure 8a is particularly useful in controlling growth in the producing of parts from wax powders, as the fusing temperature of waxes is quite close to room temperature. In addition, by controlling the gas flow rate and the temperature of the gas, the convection cooling of the target surface can be selected to also avoid curling and pitting, as can occur if the fused powder is excessively cooled.

Referring now to Figure 8b, the same apparatus is illustrated in a configuration suitable for higher temperature materials, for which growth is less of a problem

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but where curling is a problem. For such materials, it is preferred that cooling gas flow not directly impact target surface 4, so that the powder being processed thereat is not rapidly cooled, even if done uniformly. Recirculation of gas through chamber 102 may still be desirable, however, for purposes such as removal of contaminant particles and gases. This configuration is obtained by removing side panels 140, as shown in Figure 8b, so that the impedance between inlet ports 108 and the exhaust ports at outside of the top of chamber 106 is greatly reduced, particularly relative to that through diffuser 126. In this configuration, therefore, the gas flow (shown by arrows G' in Figure 8b) is directly between inlet ports 108 to the exhaust, avoiding impact of target surface 4 thereby.

15

This embodiment of the invention thus provides the further advantages of providing improved uniformity of gas flow to target surface 4, and also of providing the ability to select whether or not gas flow to target surface 4 is desired, depending upon the powder material and its fusing temperature.

Due to the improved symmetry of gas flow provided by each of the embodiments of the invention described hereinabove, it is believed that improved uniformity in cooling of each layer of powder which is processed by selective laser sintering will result. As described hereinabove, such improved uniformity of temperature enables the successful fabrication of parts made of crystalline and amorphous polymers, for example standard investment casting wax, with improved accuracy, as the temperature of the layer may be more accurately controlled over the target surface at a temperature which is optimized so as to minimize both curling and growth. This improved control of the temperature allows the fabrication of more intricate parts out of such polymer materials; as noted in the above-referenced U.S.

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6. The apparatus of claim 5, wherein said ring-shaped exhaust hood is suspended above said target surface.

7. The apparatus of claim 6, further comprising:

5 means for placing a layer of powder at said target surface, comprising a roller for pushing powder over said target surface;

means for fusing a selected portion of said layer of powder corresponding to a cross-section of the part being  
10 produced;

wherein said roller travels under said ring-shaped exhaust hood.

8. The apparatus of claim 1, wherein said means for  
15 directing gas comprises:

a fan for directing said gas into said chamber at a side wall thereof; and

a baffle, located above said target surface, having an input for receiving said gas from said fan, and having an  
20 output directed at said target surface.

9. The apparatus of claim 8, wherein said baffle is constructed in such a manner that said gas is directed in a spiraling fashion toward said target surface.

25

10. The apparatus of claim 9, further comprising:

means for placing a layer of powder at said target surface; and

an energy source for providing a focused energy  
30 beam to said powder at said target surface;

wherein said beam from said energy source passes through said baffle.

11. The apparatus of claim 10, wherein said gas is  
35 directed in a direction substantially parallel to said beam from said energy source.

12. The apparatus of claim 8, wherein said baffle is constructed in such a manner that said gas is directed at said target surface in a turbulent manner.

5

13. The apparatus of claim 1, wherein said means for directing said gas further comprises:  
means for controlling the temperature of said gas.

10

14. The apparatus of claim 1, wherein said means for directing said gas further comprises:  
means for controlling the flow rate of said gas.

15

15. The apparatus of claim 1, further comprising a radiant heater for controlling the temperature of said target surface.

20

16. The apparatus of claim 1, wherein said means for directing gas comprises:  
a plenum disposed within said chamber, having inlet ports therein, having side surfaces, and having a bottom surface with an opening therethrough over said target surface;

and wherein said exhaust means comprises exhaust plenums disposed outside of said side surfaces of said plenum, and exhaust ports in communication therewith.

30

17. The apparatus of claim 16, wherein said means for directing gas further comprises:  
a diffuser disposed within said plenum, and surrounding the opening in said bottom surface.

35

18. The apparatus of claim 16, wherein said bottom surface of said plenum comprises radiant heaters.

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19. The apparatus of claim 16, wherein said side surfaces of said plenum are removable so that gas entering said plenum through said inlet ports exits through said exhaust ports without substantially impacting said target surface.

20. A method of producing parts, comprising:  
disposing a first layer of heat-fusible powder at a target surface;  
10 scanning a selected portion of said first layer with an energy beam in such a manner as to fuse the powder thereat;

directing a flow of gas at said first layer after said scanning step;  
15 exhausting said gas from a plurality of sides of said target surface so that the direction of gas flow near said target surface is substantially parallel to the surface of said first layer;

disposing a second layer of said powder over said first layer after said scanning step; and  
20 scanning a selected portion of said second layer with said energy beam in such a manner as to fuse the powder thereat.

21. The method of claim 20, further comprising:  
controlling the temperature of said gas in such a manner that said first layer of powder is cooled by convection.

22. The method of claim 20, further comprising:  
controlling the flow rate of said gas to control the degree of convection cooling of said first layer of powder.

23. The method of claim 20, further comprising:  
35 controlling the temperature of said gas in such a manner as to cool said powder prior to said step of disposing

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said second layer to a sufficient temperature as to prevent caking of said powder.

24. The method of claim 20, further comprising:
- 5 directing a flow of gas at said second layer after said scanning thereof;
- exhausting said gas from a plurality of sides of said target surface so that the direction of gas flow near said second layer is substantially parallel to the surface of
- 10 said second layer; and
- controlling the temperature of said gas in such a manner that the temperature of said second layer is cooled to substantially the temperature of said first layer.

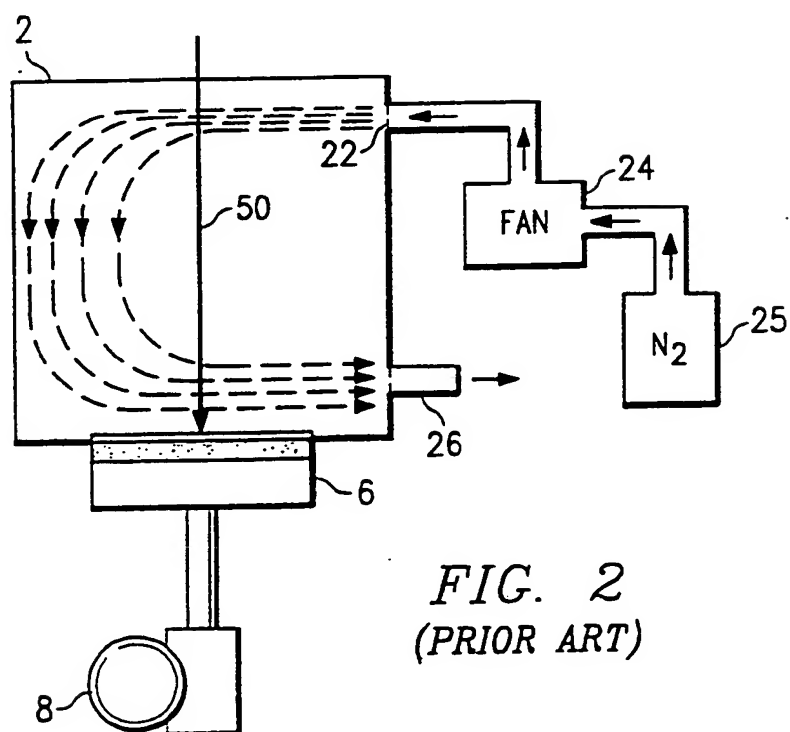
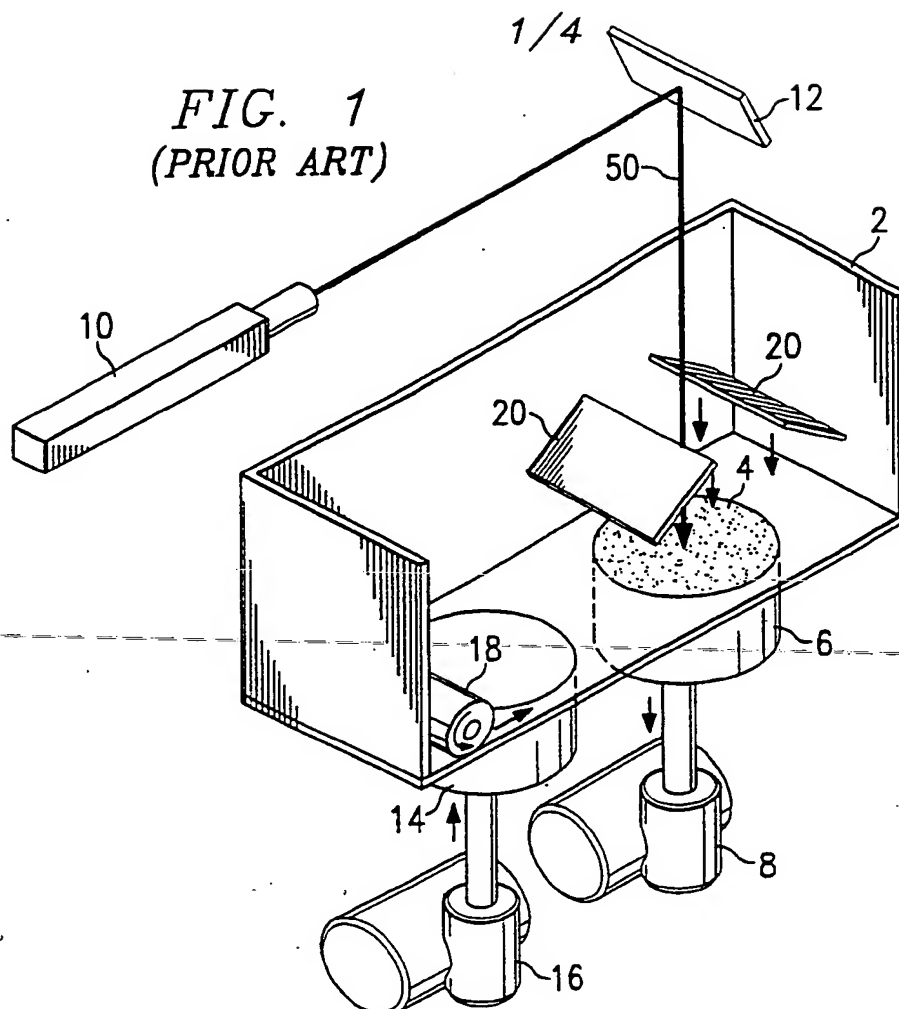
- 15 25. The method of claim 20, wherein said powder comprises a polymer.

26. The method of claim 25, wherein said powder comprises a crystalline polymer.
- 20

27. The method of claim 25, wherein said powder comprises an amorphous polymer.

28. The method of claim 25, wherein said powder
- 25 comprises investment casting wax.

\* \* \* \* \*



2/4

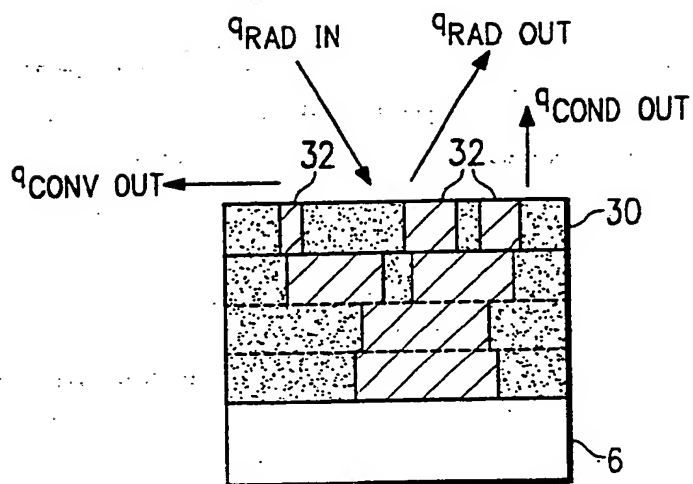
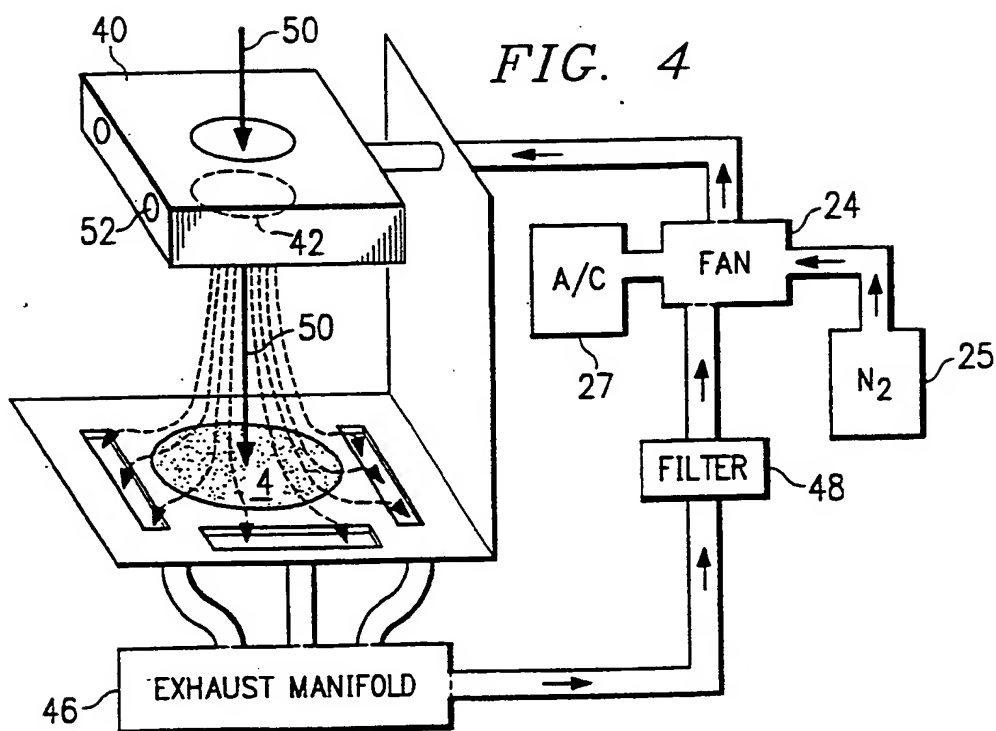


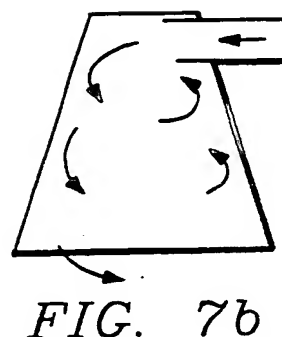
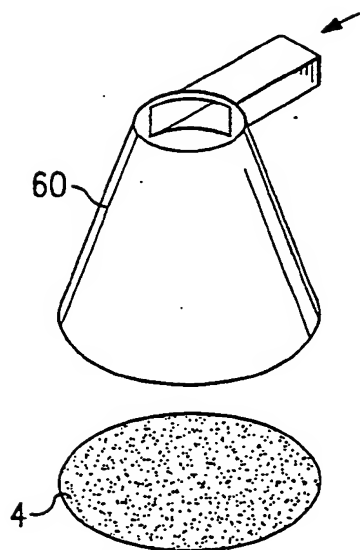
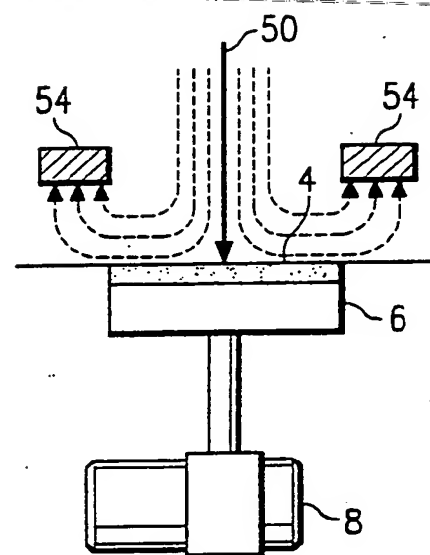
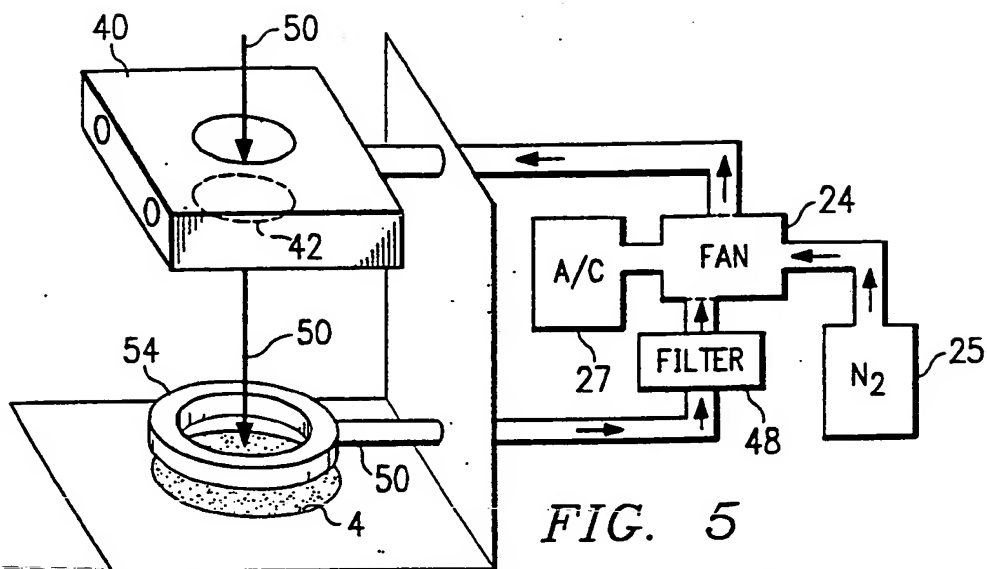
FIG. 3



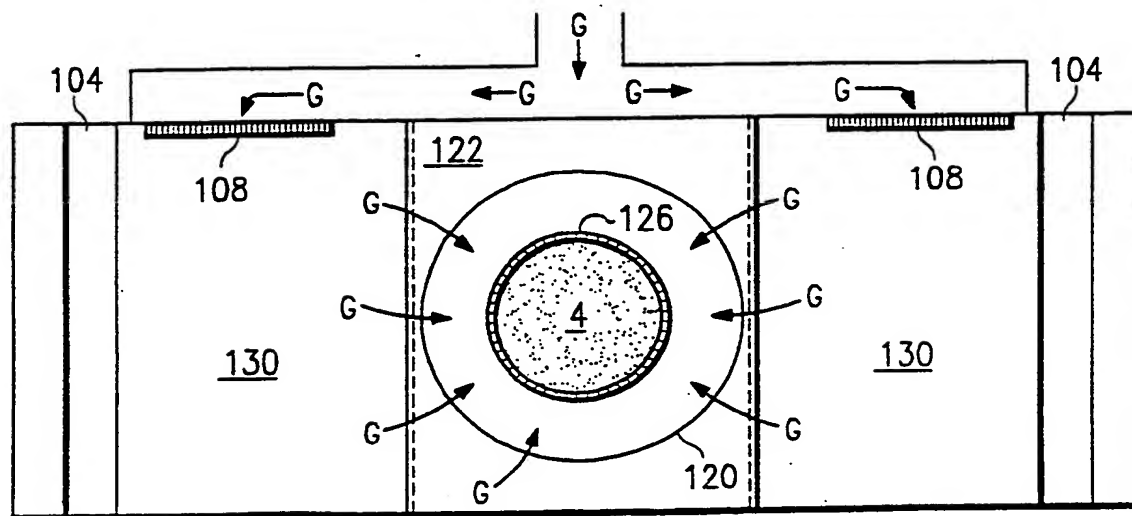
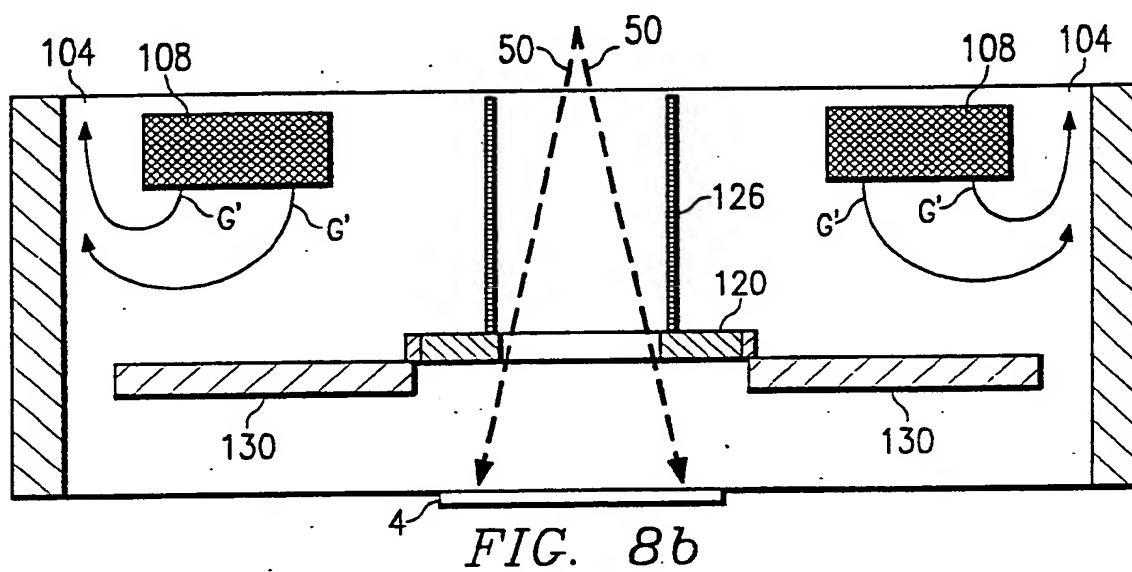
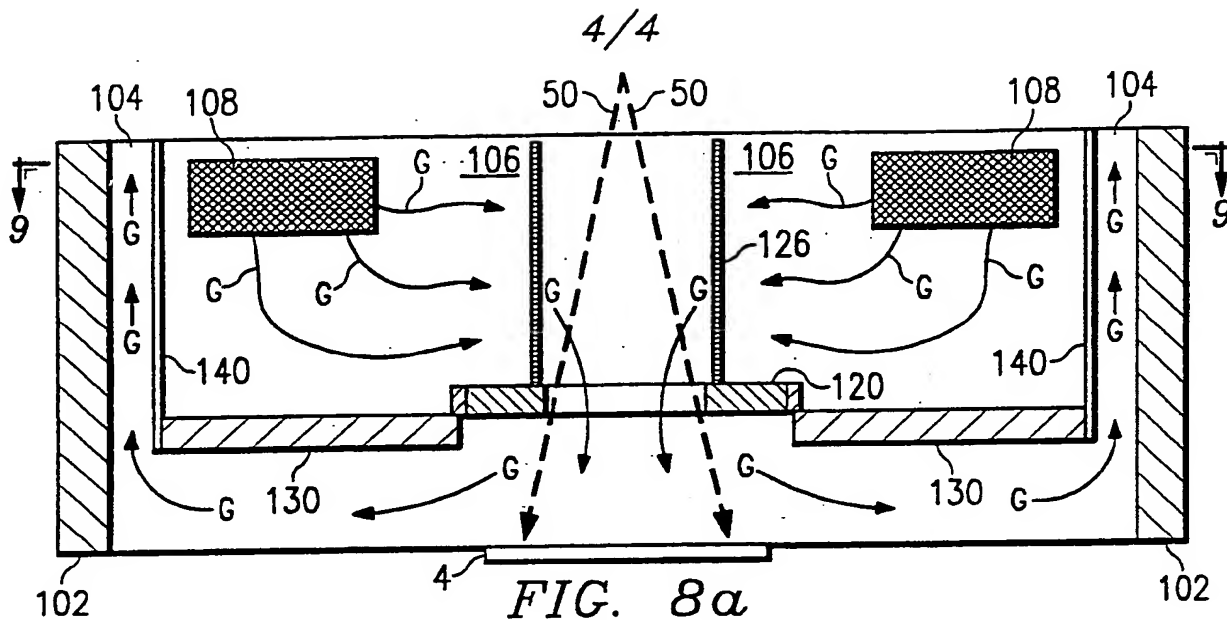
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3/4



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Patents, the formation of intricate parts is an especially beneficial use of selective laser sintering.

Besides flowing gas through the chamber for heat transfer reasons, admixtures of gases may be used to prevent oxidation, to reduce or remove oxidation products, to facilitate desirable reactions in the part being formed, or to moderate said chemical reactions and thermodynamic mechanisms. It is contemplated that the embodiments of the invention described hereinabove will be beneficial in the distribution of such gases for these purposes, as well.

While the invention has been described herein relative to its preferred embodiments, it is of course contemplated that modifications of, and alternatives to, these embodiments, such modifications and alternatives obtaining the advantages and benefits of this invention, will be apparent to those of ordinary skill in the art having reference to this specification and its drawings. It is contemplated that such modifications and alternatives are within the scope of this invention as subsequently claimed herein.

**SUBSTITUTE SHEET**

## WE CLAIM:

1. An apparatus for producing parts by way of an  
5 additive process, comprising:  
a chamber;  
a target surface in said chamber at which said  
additive process is to be performed;  
means for directing a gas at said target surface;  
10 and  
exhaust means for exhausting said gas from said  
chamber, said exhaust means positioned on a plurality of  
sides of said target surface.
- 15 2. The apparatus of claim 1, further comprising:  
means for placing a layer of powder at said target  
surface; and  
means for fusing a selected portion of said layer  
of powder corresponding to a cross-section of the part being  
20 produced.
3. The apparatus of claim 2, wherein said fusing means  
comprises:  
an energy source for providing a focused energy  
25 beam to said powder at said target surface.
4. The apparatus of claim 1, wherein said exhaust means  
comprises:  
a plurality of exhaust vents, each disposed on a  
30 side of said target surface.
5. The apparatus of claim 1, wherein said exhaust means  
comprises:  
a ring-shaped exhaust hood.

# INTERNATIONAL SEARCH REPORT

International Application No. PCT/US91/08351

<b>I. CLASSIFICATION OF SUBJECT MATTER</b> (if several classification symbols apply, indicate all) <sup>6</sup>		
According to International Patent Classification (IPC) or to both National Classification and IPC		
IPC (5): B29C 35/08		
U.S.CI.: 425/174.4; 156/272.8, 379.6; 219/121.84; 264/22		
<b>II. FIELDS SEARCHED</b>		
Minimum Documentation Searched <sup>7</sup>		
Classification System	Classification Symbols	
U.S.	425/73, 74, 143, 174, 174.4; 219/121.63, 121.64, 121.84; 156/62.2, 272.8, 379.6, 380.9, 500; 264/22, 25, 40.6, 85, 125-127, 308	
Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched <sup>8</sup>		
<b>III. DOCUMENTS CONSIDERED TO BE RELEVANT <sup>9</sup></b>		
Category <sup>10</sup>	Citation of Document, <sup>11</sup> with indication, where appropriate, of the relevant passages <sup>12</sup>	Relevant to Claim No. <sup>13</sup>
Y	WO, A, WO 88/02677 (DECKARD) 21 April 1988 See Figures 10, 11, reference numerals 12, 116, 136, 140, 148.	1-28
Y	US, A, 4,642,445 (STOL) 10 February 1987 See Figures 2-4, reference numerals 323, 333.	1-28
A	US, A, 4,835,357 (SCHALK) 30 May 1989 See the entire document.	1-28
A	US, A, 4,945,207 (ARAI) 31 July 1990 See the entire document.	1-28
<p><sup>10</sup> Special categories of cited documents:</p> <p>"A" document defining the general state of the art which is not considered to be of particular relevance</p> <p>"E" earlier document but published on or after the international filing date</p> <p>"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)</p> <p>"O" document referring to an oral disclosure, use, exhibition or other means</p> <p>"P" document published prior to the international filing date but later than the priority date claimed</p> <p>"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention</p> <p>"X" document of particular relevance: the claimed invention cannot be considered novel or cannot be considered to involve an inventive step</p> <p>"Y" document of particular relevance: the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.</p> <p>"d" document member of the same patent family</p>		
<b>IV. CERTIFICATION</b>		
Date of the Actual Completion of the International Search		Date of Mailing of this International Search Report
31 January 1992		19 MAR 1992
International Searching Authority		Signature of Authorized Officer
ISA/US		Richard L. Chiesa

